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Modelling of Restriking and Reignition Phenomena in Three-phase Capacitor and Shunt Reactor Switching

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ABSTRACT

Capacitor banks and shunt reactors are frequently switched by circuit-breakers in medium voltage (MV) and high voltage (HV) electricity networks. In recent years there have been explosive failures due to circuit-breaker restriking and reignition consequently there is a need for monitoring techniques that will facilitate the identification and quantification of the onset of more severe restriking. Whilst there has been detailed analyses of single-phase shunt reactor and capacitor bank switching there is a paucity of information about restriking phenomena and reignition in three-phase circuits for the correlation of system problems with specific waveform characteristics to develop the necessary identification algorithms for proactive monitoring of circuit-breakers' condition. This paper describes the modelling restriking and reignition occurring during three-phase capacitor bank and shunt reactor switching using the Alternative Transients Program (ATP) and network data from AS 4372-1996. Information from the ATP models and data resulting from the simulations are examined with a view to developing an intelligent diagnostic system with logging and alarm features. This modelling method can be easily applied with different data from the different dielectric curves, circuit breakers and networks.

1. INTRODUCTION

Capacitor banks and shunt reactors are frequently switched in medium voltage (MV) and high voltage (HV) electricity networks, since their connection to the networks is essential for reactive compensation reasons, improving the power quality locally.

The term "restrike" is defined as a re-establishment of the current, one-quarter cycle or longer, following interruption of a capacitive current at a normal current zero [1]. A reignition occurs when a current is interrupted at current zero and then re-establishes itself within one-eight of a power frequency cycle [2]. Whilst there has been detailed analyses of single-phase capacitor bank and shunt reactor switching [3], [4], and [5], there is a paucity of information about restriking and reignition phenomena in three-phase circuits for the correlation of system problems with specific waveform characteristics to develop the necessary identification algorithms for proactive monitoring of circuit-breakers' condition [6]. In this paper, the possibly prejudicial phenomena caused by the switching of capacitor banks and shunt reactors are presented with the modelling of restriking and reignition occurring during three-phase capacitor bank and shunt reactor bank switching using the Alternative Transients Program (ATP). Information from the ATP models and data resulting from the simulations are examined with a view to developing an intelligent diagnostic system with logging and alarming features for online monitoring of circuit-breakers.

Section 2 provides ATP simulation results and comparing these with simple formulae. Section 3 covers the methodology and applications. Section 4 is devoted to discussion, while conclusions are presented in Section 5.

2. ATP MODEL OF THE SYSTEM AND DATA

2.1 Capacitor Bank Switching Modeling

Example system parameters used in ATP simulation studies are as follows:

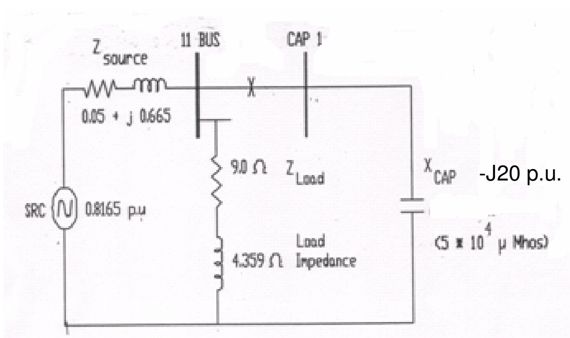

Figure 1. Capacitor Bank Single-phase Equivalent Circuit

The above figure 1 shows a single-phase equivalent circuit for a capacitor bank and which is simulated using the ATP program on a single-phase and also a three-phase grounded capacitor bank switching circuit.

In this paper a 5MVAr (-j20p.u.) capacitor bank 11kV bus at a zone substation with a 150MVA fault level with a load of 10MVA @0.9 p.f. lag was studied.
The major circuit parameters are:

- Source resistance R1= 0.05 Ω, inductance X1 =0.665 Ω or L1=2.11676mH at 50Hz
- Damping resistance = 100 Ω provides damping source transient
- Bus stray shunt capacitance C1=2.63nF
- Shunt capacitance to ground C2 = 63.662nF or 5MVar) capacitor bank
- High resistances around switch to damp numerical oscillations 10000 Ω
- Discharge resistor R2=1000 Ω

The first switch to close at the start of the simulation, and open after 20 ms. This de-energises the capacitor current being interrupted it at a natural current zero. The second switch is set to simulate a reignition (i.e. a voltage controlled switch) so that flashover occurs when the voltage across it reaches 1.5 p.u. It was noted that the switch opening was set at 0.02 second and the switch closing was set at 0.03 second for closing operation, both switch opening and switch opening with restrikes were set at 0.02 second. For simulation of opening restrikes the time delay was 0.0008 second for trapped charge, whereas for both the time delay for capacitance switching on closing and opening the time delay was 20 seconds for no trapped charge. Other circuit-breaker (CB) models such as dielectric recovery and arc resistance may be applied.

The ATP simulation waveforms are:

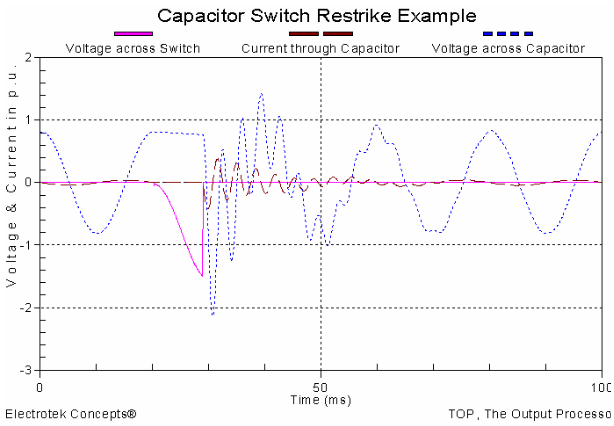

Figure2. Single-phase restrike waveform

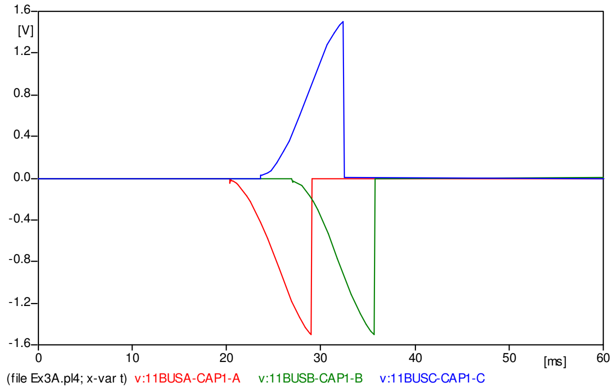

Figure 3. Three-phase single restrike waveform

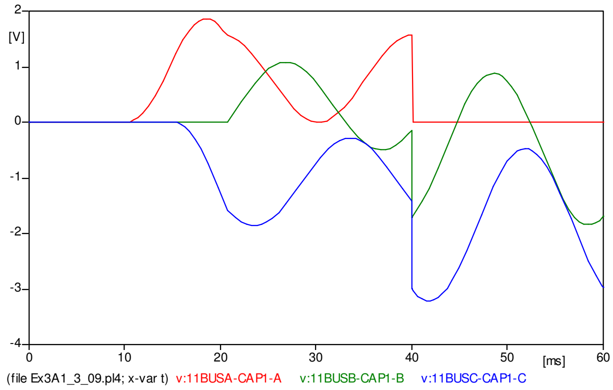

Figure 4. Three-phase two restrikes with voltage escalation waveform

As can be seen from Figure 2 current in the capacitor is interrupted at a negative-going current zero at 20ms. This interruption leaves a d.c. voltage on the capacitor bank and results in a voltage with a d.c. and a.c. component appearing across the circuit-breaker with single restrike. Two restrikes are obtained to adjust the current in the capacitor is interrupted at a negative-going current zero at 10ms.

TRV oscillating frequency $$f = \frac{1}{2\pi\sqrt{(L_1 C_1)}} \quad (1)$$

Inrush current $$I_{peak} = \frac{V_{peak}}{\sqrt{\frac{L_1}{C_2}}} \quad (2)$$

Using equation (1) the bus-bar capacitance C_1 is calculated with source inductor L_1 and the TRV oscillating frequency f_0 ranges from 10kHz to 50MHz [7] for restrike overvoltages. Transient Recovery Voltage (TRV) is relevant for the small amplitude oscillation occurring on the supply side of the CB when the CB opens. The computer simulation as per Figure 2 produces very similar waveforms in good agreement with the measured waveforms from literature such as a capacitor bank energisation given in references[5]. The same are also validated using the formulae.

Table 1: The Comparison of Using the Formulae and Computer Simulation for Grounded Capacitor Bank

Method	Inrush Current (kA)	Oscillation Frequency (kHz)	Transient Recovery Voltage (p.u.)
Using the formulae given in (1), (2) and [8]	0.53	6.74	1.4
ATP Computer Simulation	0.55	7.00	1.5
% discrepancy	4.4	3.7	6.7

2.2 Shunt Reactor Modelling

There are different parameters for the shunt reactor model simulation, depending on different type of circuit breakers such as vacuum circuit breaker chopping current calculated by Smeets [9] and the dielectric strength of the breaker gap [10] as well as the contact separation. The dielectric strength gap or the contact separation depends on the rate of the rise of the recovery voltage, which occurs to the opening contact-system. This varies with the help of the ATP statistic switch.

A three-phase equivalent circuit with Dielectric Strength Reset Model used in the ATP is given in Figure 5. But the installation includes the shunt reactor bank (consists of three 120MVAr single phase reactor).

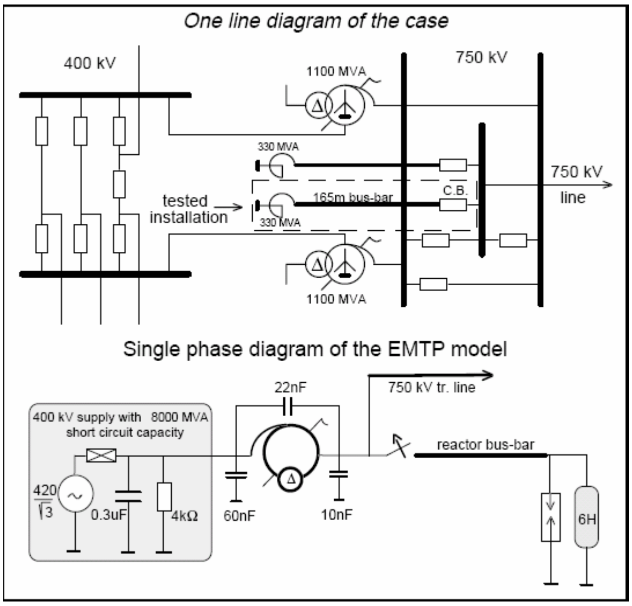

Figure 5. Shunt Reactor Switching [11]

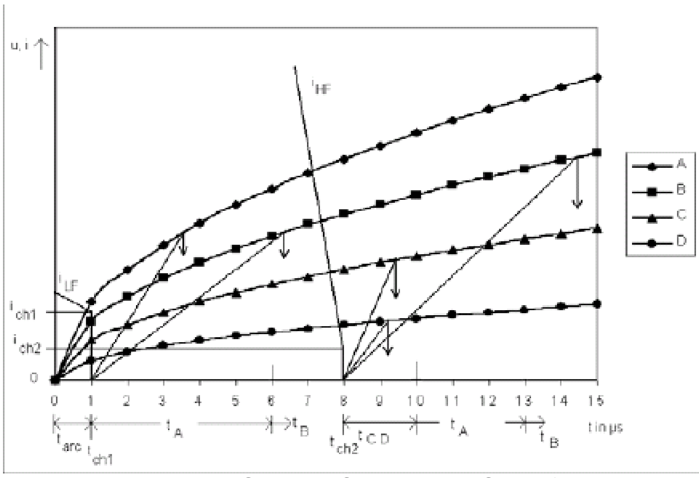

Figure 6. Dielectric Strength Curves A, B, C, D After Current Interruption[12]

The used values of the curves and times in the model were taken from literature data [13] and the network data is taken from with [14].

The 400kV with short-circuited current 60kA gives

Inductance= $400/\sqrt{3}x60 = 3.85\ \Omega$ or 12.3 mH i.e. less than 10% of shunt reactor inductance

Source capacitance= 0.03 µF i.e more than 10 times load capacitance

Reactor capacitance = 1.9nF

Reactor inductance = 2.55H

Reactor resistance with 173A = 1330 Ω

Circuit-breaker models: the MODEL language in ATP with the TACS switch was used to realise an accumulator and logic operators for the reignition control, where the recovery voltage is larger than the dielectric recovery voltage after the current chopping, a voltage comparator is applied subsequently.

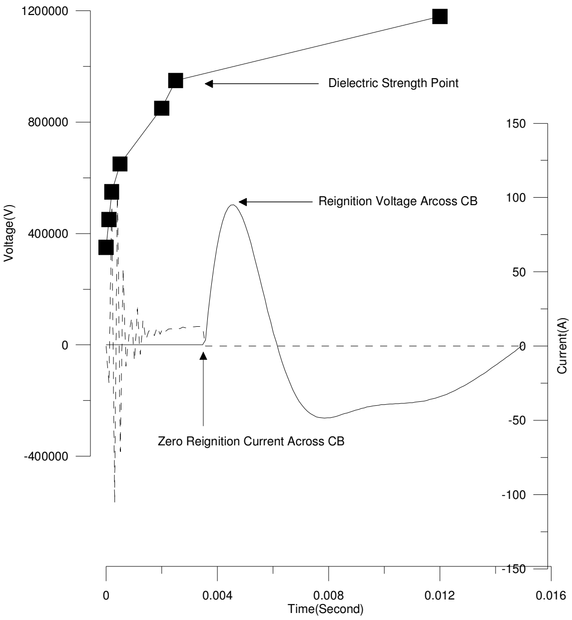

Figure 7. Single Reignition Across Circuit-breaker

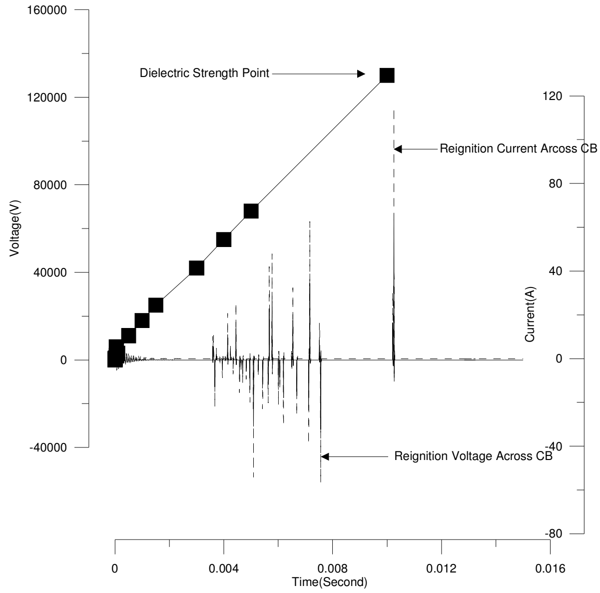

Figure 8. Multiple reignitions Across Circuit-breaker

Dielectric reignition is produced by breakdown of the open gap in a circuit-breaker operation. In practice this is due to the cooling of the hot gases between the two contacts of the circuit-breaker until results in a dielectric reignition are of the type shown in Figure 6. Depending on the ignition-delay, higher values were reached by a higher rate of the rising of the recovery voltage. Flashover in hot gas between the zero interruption current cause reignition current for the single-phase case. The multiple reignitions are obtained from the appropriate dielectric curve gradient as shown in Figure 8.

Simulation results and verification: The ATP model described above has been verified using the formulae with the following results:

Table 2: Comparison of calculated and simulated overvoltages and frequency [11]

	Phase-to-ground overvoltage* (kV)	Frequency*(kHz)
ATP simulation	320	28
Using the formulae given in [15]	350	29
% discrepancy	11.8	3.5

*The data refer to the first interruption phase

By adjusting the gradient of the dielectric curve, single and multiple reignitions were obtained as per Figure 7 and Figure 8 for single-phase shunt reactor switching. With the help of a random generator in ATP, numbers in the interval [0, 1] were defined for the scattering process like chopping current, regnitions and the characteristics of the recovery voltage. Three-phase with statistical switching case using formula for ATP programming is taken from formula 26.2.23, page 933[16]. A three-phase equivalent circuit with Dielectric Reset Model used in the Figure 5 and three-phase waveforms were shown as follows.

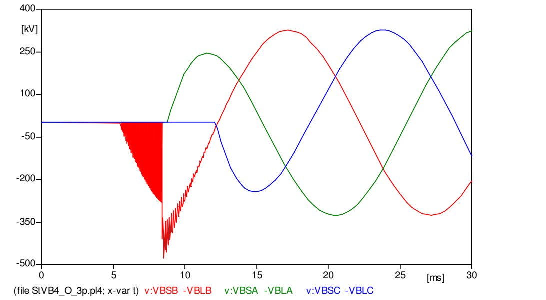

Figure 11. Three-phase Voltage Across Circuit-breaker With Statistical Figure Simulation

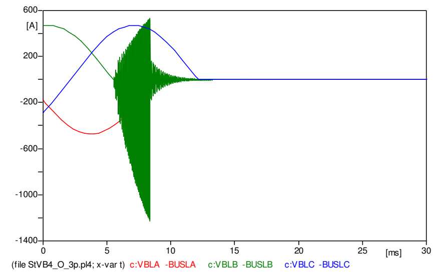

Figure 12. Three-phase Current Arcoss Circuit-breaker With Statistical Figure Simulation

The computer simulations as per Figures, 7 , 8, 11 and Figure 12 produces very similar waveforms in good agreement with the measured waveforms from literature for shunt reactor switching given [11]. The same are also validated using the formulae.

3. METHODOLOGY AND PRACTICAL APPLICATIONS

In this computer simulation study, the voltage across the circuit-breakers of the capacitor banks and shunt reactors provide electrical signatures.

The factors are important to characterize each type of circuit network such as ddifferent type of switching transient such as circuit breaker, network and dielectric strength curve parameters. The results are:

- Three-phase voltage across circuit-breaker voltage waveform for capacitor bank switching and shunt reactor switching (Figures 3,4, 11 & 12)
- Practical applications with electrical signature analysis to identify different features for capacitor bank switching with Fourier Transform. (Figures 9 & 10)

The complexity of the classification cannot be fully explained in a digest. But some brief examples of electrical signature analysis are given below:

Type 1: Single restrike for capacitor bank switching

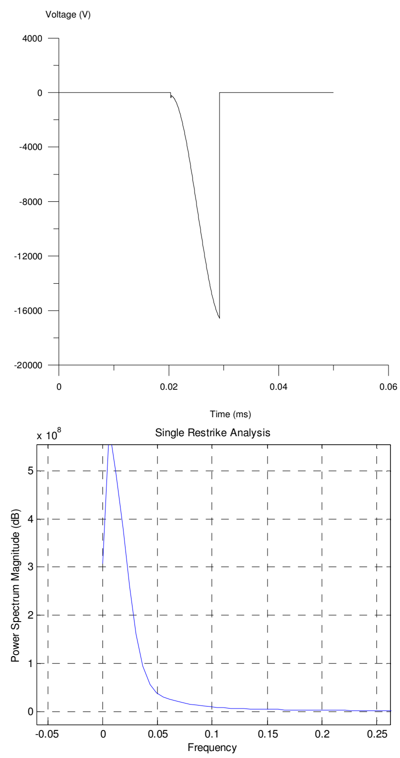

Figure 9. Power Special Density Plots shows the strength of the single restrike (energy) as a function of frequency

Type 2: Two restrikes for capacitor bank switching

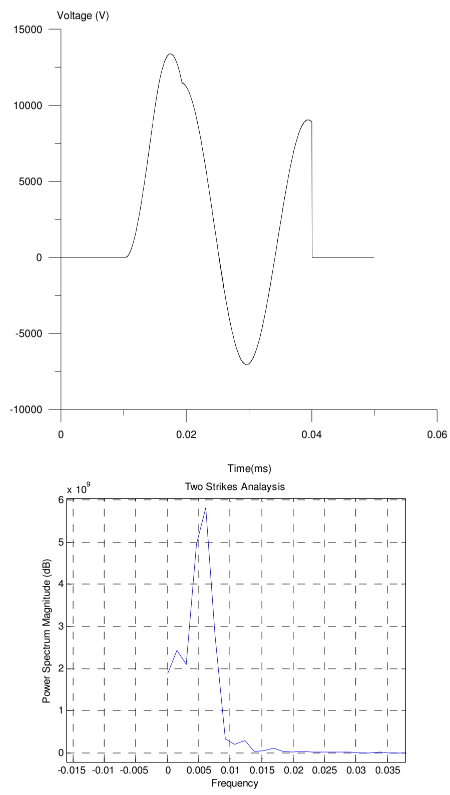

Figure 10. Power Special Density Plots shows the strength of the two restrikes (energy) as a function of frequency

Figures 9 & 10 show different signatures such as single restrike and two restrikes for analysis of restriking waveforms. Power spectral density function (PSD) shows the strength of the variations (energy) as a function of frequency. This might be able to get a clue to locate dielectric strength deterioration by looking at PSD which would give us frequencies of restriking/reignition. The data from ATP simulations are applied in MATLAB, and the same simulated results from different conditions are used for a range of high voltage network conditions for the Self-Organising Map (SOM) training data. A dielectric strength deterioration index k is defined to measure the difference between the discrepancy/errors for severe restriking or reignitions and the discrepancy/errors normal restriking or reignitions, which is used for a quantitative trend index for the circuit breaker condition.

$$k = \frac{E(severe)errors/discrepancy}{E(normal)errors/discrepancy} \qquad (3)$$

4. DISCUSSION

It is seen that the transient waveforms are different for network and dielectric strength parameters for capacitor bank switching and shunt reactor switching. This is characterised by a step change in the voltage, followed by an oscillation as the voltage across the circuit-breaker equalizes within the system voltage. The oscillation occurs at the natural frequency of the capacitor with the inductance of the power system.

Virtual current chopping is caused by an interaction between two phases A and C, dependent upon the capacitive coupling between the phases. Different reignition results were obtained due to the dielectric strength with different statistical figures for ATP simulations as shown in Figures 11 & 12.

Other methods are Fourier and Wavelet analysis which could be used to identify a different signature and distinguish it from other transient disturbance [17]. The modelling method can be readily applied to getting the features for restrikes and reignitions with adjustable parameters, as long as the network, dielectric strength curve and circuit breaker data are available. If the data are not available, alternative methods need to be used such as field measurement.

5. CONCLUSION

Based on the analysis of frequency range 10kHz to 500MHz for restrike overvoltages due to different source inductance and capacitance using equation (1) for capacitor switching, and different dielectric strength gradient curves and the network data from [14] with different statistical figures for multiple reignitions, we propose a simple parallel switch model for capacitor switching restrikes and a dielectric reset model to simulate multiple reignitions while taking with statistical effects into consideration and the framework for taxonomy of electrical signatures. The proposed taxonomy can be used to develop an intelligent diagnostic system with logging and alarm features. It is envisaged that such taxonomy would evolve continuously with future changes of network topology. Different virtual current chopping features for three-phase shunt reactor switching were obtained due to an interaction between two phases A and C, which is also dependent upon the capacitive coupling between the phases for ATP simulation.

The framework proposed here, however, forms the basis for individual circuit-breaker signature and taxonomy study. Action research is being carried out to use Wavelet Analysis for features extraction. Although the overvoltage estimations of the capacitor bank switching and shunt reactor switching have been checked by formulae to confirm the validity of the ATP studies, many scenarios are really required to simulate for the development of a database for on-line monitoring. However, the sensitivity analysis studies and the validation of the waveforms were not easy to implement without data from real utility scenarios.

REFERENCES

[1] N. E. Dillow, I. B. Johnson, N. R. Schultz, and A. E. Were, "Switching Capacitive Kilovolt-Amperes with Power Circuit Breakers," *AIEE Transactions*, pp. 188--200, 1952.

[2] R. D. Garzon, *High Voltage Circuit Breakers: Design and Applications*: Marcel Dekker, Inc., 1996.

[3] Z. Ma, C. A. Bliss, A. R. Penfold, A. F. W. Harris, and S. B. Tennakoon, "An investigation of transient overvoltage generation when switching high voltage shunt reactors by SF6 circuit breaker," *IEEE Transactions on Power Delivery*, vol. 13, pp. 472-479, 1998.

[4] S. M. Wong, L. A. Snider, and E. W. C. Lo, "Overvoltages and reignition behaviour of vacuum circuit breaker," *International Conference on Power Systems Transients - IPST 2003 in New Orleans, USA*, pp. 1-6, 2003.

[5] D. V. Coury, C. J. dos Santos, and M. C. Tavares, "Transient analysis resulting from shunt capacitor switching in an actual electrical distribution system," presented at Harmonics And Quality of Power, 1998. Proceedings. 8th International Conference on, 1998.

[6] M. Waclawiak, M. McGranaghan, and D. Sabin, "Substation power quality performance monitoring and the Internet," presented at Power Engineering Society Summer Meeting, 2001. IEEE, 2001.

[7] M. Kizilcay, "Power System Transients and Their Computation Chapter 1," in *University of Applied Science of Osnabruk, Department of Electrical Engineering and Computer Science*. Albrechtstr, 30, D-49076 Osnabruck Germany.

[8] I. B. Johnson, A. J. Schultz, N. R. Schultz, and R. B. Shores, "Some Fundamentals on Capacitance Switching," *AIEE Transaction*, pp. 727-736, 1955.

[9] R. P. P. Smeets, "Essential Parameters of Vacuum Interrupter and Circuit related to Occurence of Virtual Current Chopping in Motor Circuits," *International Symposium on Power and Energy, Sapporo, Japan*, 1993.

[10] M. Popov, "Switching Three-Phase Distribution Transformers with a Vacuum Circuit Breaker Analysis of Overvoltages and the Protection of Equipment," in *Delft University of Technology*. The Netherlands, 2002.

[11] L. Prikler, G. Ban, and G. Banfai, "EMTP models for simulation of shunt reactor switching transients," *Electrical Power & Energy Systems Elsevier Science Ltd.*, vol. 19, pp. 235-240, 1997.

[12] M. M. Saied, E. A. Oufi, and E. E. El-Attar, "Theoretical and experimental investigations on circuit breaker transient recovery voltages," presented at Power Systems and Power Plant Control 1989. Selected Papers from the IFAC Symposium, Seoul, South Korea, 1990.

[13] Z. Ma, "Reactor Current Switching With Gas Blast Circuit Breakers," Stafford University, 1996.

[14] "High-voltage switchgear and control gear Inductive Load Switching," Australian Standard AS62271.1.110-2006.

[15] "High voltage alternating current circuit breakers-inductive load switching," IEC Technical Report No. 1233, 1993.

[16] Abramowitz and a. Stegun, *Handbook of Mathematical Functions*, 2000.

[17] S. Santoso, W. M. Grady, E. J. Powers, J. Lamoree, and S. C. Bhatt, "Characterization of Distribution Power Quality Events with Fourier and Wavelet Transforms," *IEEE Trans. Power Delivery*, vol. 5, pp. 247-254, Jan. 2000.